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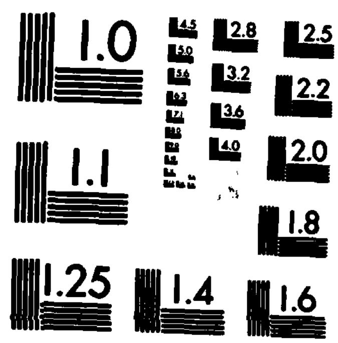

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FINAL REPORT

Survey of Atmospheric Radiation Components

for the

Gamma and Cosmic Ray Astrophysics Branch

of the

Space Science Division

of the

Naval Research Laboratory

Prepared by

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Contract Number N00014-83-C-2042

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Introduction

This is a final report of research done for the Gamma and Cosmic Ray Astrophysics Branch, Space Science Division, Naval Research Laboratory under contract #N00014-83-C-2042. The work was performed by Severn Communications Corporation, Severna Park, Maryland from 15 Dec 1982 through 15 Jan 1984. The principal investigator was Dr. John R. Letaw.

The objects of this study, as set forth in the Statement of Work, were:

(1) Conduct a comprehensive literature search to determine the state-of-the-art knowledge of the effect of atmospheric radiation components on semiconductor materials from sea level to the top atmospheric layers. Emphasis shall be placed on particle propagation, radiation effects on semiconductor materials, and methods of calculating nuclear reaction cross sections. A comprehensive survey shall be made on the interactions between atmospheric components and cosmic rays and the secondary emissions and energy spectra produced.

(2) Generate propagation algorithms to describe the penetration of primary cosmic rays into the atmosphere and the production of secondary emissions.

(3) Calculate the energy loss rates in semiconductor materials for various cosmic ray components as a function of altitude, geomagnetic location, and zenith and azimuthal angles.

The work completed under this contract is summarized in this and the next two sections of this Final Report. Detailed descriptions of the results have been published in a number of journal articles and reports. Copies of these papers are attached to this Final Report. Publications written and published (or substantially completed) during the contract period were:

"Propagation of Heavy Cosmic Ray Nuclei"
(with R. Silberberg and C.H. Tsao)
(submitted to Astrophysical Journal Supplements)

"Improved Cross Section Calculations for Astrophysical Applications"
(with R. Silberberg and C.H. Tsao)
(submitted to Astrophysical Journal Supplements)

"On the Abundances of Ultraheavy Cosmic Rays"
(with R. Silberberg and C.H. Tsao)
(to appear in Astrophysical Journal)

"Radiation Doses and LET Distributions of Cosmic Rays"
(with R. Silberberg, C.H. Tsao, and J.H. Adams)
(to appear in Radiation Research)

"Cosmic Ray Transport in the Atmosphere: Dose and LET Distributions in Materials" (with R. Silberberg, C.H. Tsao, and J.H. Adams)
IEEE Transactions on Nuclear Science,NS-30,4398 (1983)

"LET Distributions and Radiation Doses due to Cosmic Rays"
(with R. Silberberg, C.H. Tsao, and J.H. Adams)
IEEE Transactions on Nuclear Science,NS-30,4405 (1983)

"Proton Production Cross Sections in Proton-Nucleus Collisions"
Physical Review,C28,2178 (1983)

"Distributed Acceleration of Cosmic Rays"
(with R. Silberberg, C.H. Tsao, and M.M. Shapiro)
Physical Review Letters,51,1217 (1983)

The following reports and/or conference papers were delivered during the contract period:

"Cosmic Ray Effects on Microelectronics, Part III: Cosmic Rays in the Atmosphere" (with R. Silberberg, C.H. Tsao, and J.H. Adams)
NRL Memorandum Report (in press)

"Cosmic Ray Effects on Microelectronics, Part II: The Geomagnetic Cutoff Effects" (with J.H. Adams and D.F. Smart)
NRL Memorandum Report 5099 (1983)

"Cosmic Ray Background in a GRO Detector"
(with R. Silberberg and C.H. Tsao)
NRL Space Science Division Science and Engineering Memorandum (1983)

"Models for Cosmic Ray Propagation at Energies 10^8 - 10^{14} eV"
(with R. Silberberg, C.H. Tsao, and M.M. Shapiro)
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),2,179 (1983)

"Total and Partial Inelastic Cross Sections of Proton-Nucleus Reactions" (with C.H. Tsao and R. Silberberg
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),2,194

"Implications of the Ratio $(61 < Z < 75)/(76 < Z < 83)$ on the Origin and Propagation of the Ultraheavy Cosmic Rays"
(with C.H. Tsao, R. Silberberg, and J.H. Adams)
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),2,225

"Propagation and Origin of Energetic Cosmic Rays 10^{14} - 10^{19} eV"
(with R. Silberberg, C.H. Tsao, and M.M. Shapiro)
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),2,283

"Radiation Doses and Biological Effects of Cosmic Rays"
(with R. Silberberg, C.H. Tsao, and J.H. Adams)
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),2,398

"Propagation of Cosmic Rays in the Atmosphere and Energy Deposition in Detectors"
(with C.H. Tsao, R. Silberberg, and J.H. Adams)
Proc. 18th Int. Cosmic Ray Conf. (Bangalore),5,380

"Origin, Propagation and Interactions of Cosmic Rays with $76 < Z < 83$" (with C.H.Tsao, R. Silberberg, and J.H. Adams)
Bulletin of the American Physical Society,28,754 (1983)

"Models for High Energy Cosmic Ray Propagation"
(with R. Silberberg, C.H. Tsao, and M.M. Shapiro)
Bulletin of the American Physical Society,28,754 (1983)

"Partial Inelastic Cross Sections for Cosmic Ray Propagation Calculations" (with R. Silberberg and C.H. Tsao)
Bulletin of the American Physical Society,28,754 (1983)

In addition to the papers developed under this contract a number of computer programs have been written to produce published results. These programs have been designed for personal use and are of limited value to members of the Cosmic Ray Astrophysics Section. Many of the programs and subroutines have been exchanged informally with that group.

Propagation of High Energy Ions in Matter

The general problem faced in this section is to predict the change in a flux of high energy ions (neutrons, protons, and heavy nuclei) as it passes through various types of matter and to predict the effects of this radiation on the matter it is passing through. The particles of interest in these computations are cosmic rays and solar flare particles with energies greater than about 1 MeV/nucleon. These propagations require careful treatment of energy loss and nuclear fragmentation since both are important in determining the resulting charge and energy spectrum of the flux. The propagations in matter are executed in three stages, each of which is described further below:

A. Modeling and determination of the incident particle flux.

B. Propagation of the incident flux through layers of matter specified by density and chemical composition.

C. Post-processing of the resultant flux, integrating over angle and/or evaluating radiation effects.

The cosmic ray flux outside the heliosphere consists of nuclei of all elements in the periodic table, excepting short-lived transuranics. The composition is similar to that of the solar system as slightly modified by 10 million years passage through the interstellar medium. This flux remains essentially isotropic as it passes through the heliosphere and joins anisotropic fluxes of energetic solar particles and trapped ions. Upon reaching Earth's magnetosphere many of these particles are deflected in a manner dependent upon their energy, trajectory, and charge-to-mass ratio. This geomagnetic cutoff effect essentially truncates the low energy parts of the spectrum, hence only at high latitudes do low energy cosmic rays penetrate satellite orbits and the atmosphere. The steps involved in modeling the incident particle flux are:

1. Model composition of cosmic ray sources

   i. Galactic cosmic rays in the heliosphere
   ii. Solar energetic particles
   iii. Trapped ions

2. Modify flux according to geomagnetic transmittance

   i. For a single location and particle direction truncate spectrum according to geomagnetic cutoff.
   ii. For an orbiting spacecraft modify spectrum according to orbit-averaged geomagnetic cutoff along an axis fixed with respect to the spacecraft.

As stated above, the cosmic ray flux is altered by energy loss and nuclear fragmentation as it passes through matter. It is the purpose of the propagation programs to follow the changes in energy and charge spectra. Energy loss in matter is due primarily to ionization of the medium. A few hundreds of eV may be lost in any collision, thus at high energies this loss may be modeled by a smooth energy loss rate, the stopping power. Nuclear fragmentation is dependent on total and partial fragmentation cross sections. The total cross section is the probability of a destructive collision between the incoming cosmic ray and the medium. The partial cross sections determine the relative numbers of each fragment produced. Thus these steps are required in propagating the incident flux:

3. Satisfy atomic and nuclear data requirements

   i. Model the total and partial fragmentation cross sections of any nucleus-nucleus collision as a function of energy.
   ii. Model the stopping power of any ion in any stopping medium (elementary or compound) as a function of energy.

4. Develop numerical techniques for propagation calculations.

The final step in propagation through matter is post-processing. Many computational uses for the flux of cosmic rays after passing through various layers of matter can be found. We have concentrated on determining the effects on semiconductors (single-event upsets) and on people (radiation dose). In both cases the rate of energy deposition in matter (silicon or water), not the total cosmic ray energy, is the essential factor in estimating radiation effects. In the case of effects in the atmosphere, it is first necessary to compute the cosmic ray flux integrated over all directions. Thus we have the following post-processing options:

5. Integrate over angles to determine flux average if directionality is not being investigated

   i. In atmosphere average over zenith and azimuthal angles
   ii. For radiation dose average over spherical phantom

6. Compute single-event upset rate

   i. Compute device-independent LET spectrum
   ii. Fold in device-dependent sensitivity and pathlength distribution

7. Compute radiation dose

   i. Compute dose in rads
   ii. Compute dose equivalent in rems

Work under the present contract has yielded many results concerning cosmic ray fluxes in the atmosphere and in space, and their effects on microelectronics and biological systems. There are, however, many deficiencies in the current structure of programs to calculate high energy ion propagation in matter. Because of these deficiencies, many useful calculations cannot be made and the accuracy of some of the results is much lower than necessary.

The determination of the incident cosmic ray flux is limited to a great extent by available experimental data. Examples are uncertainty concerning the relation between solar activity and low energy particle fluxes, unpredictability of solar flare composition and frequency, and ignorance of trapped heavy ion fluxes. A model of the particle environment was proposed by the NRL Laboratory for Cosmic Ray Physics in 1981. Some limitations and inconsistencies in that model have been found in our work. A new, more flexible model of the cosmic ray environment would allow higher accuracy to be maintained in propagation computations.

The programs we currently have available for orbit-averaged geomagnetic transmittance calculations are limited to vertical cutoffs (see "Cosmic Ray Effects on Microelectronics: Part II"). Since this report was published we have extended the programs to include elliptical orbits. An extension of the programs to compute cutoffs along any fixed direction within a rotating spacecraft would be a valuable aid in detailed radiation effects calculations.

A major limitation of current propagation programs is the lack of adequate models for total and partial fragmentation cross sections of nuclei on nuclei. Small errors in these cross sections are magnified many times in propagation down to 50,000 feet in the atmosphere. Current models of total cross sections do not account for energy dependence and are based on little experimental data. Partial cross section models are modified versions of semiempirical proton-nucleus cross section models and thus begin with at least 30% error. During the present contract period we have extended the validity of some cross section computations in "Proton Production Cross Sections in Proton-Nucleus Collisions".

Galactic Propagation of Cosmic Rays

While the study of cosmic ray propagation in the galaxy is of little direct importance in understanding radiation effects on biological and electronic systems, many of the techniques and data requirements are identical. These tools, which are essential in any high energy ion propagation, are available almost exclusively in the cosmic ray literature. We cannot overemphasize the importance of maintaining strong ties with the cosmic ray community and keeping abreast of the cosmic ray literature as a stimulus for significant progress in understanding radiation effects. Our work in the field of galactic propagation has led to new models of nuclear interactions as well as a more accurate identification of important atomic processes (such as electron stripping and attachment).

Some of the data requirements for galactic propagation are not so severe as the case of general propagation in matter. For example, in galactic propagation only proton-nucleus fragmentation cross sections, not the general nucleus-nucleus cross sections, are needed. The discipline is, however, typically more exacting. In computing radiation effects only elemental composition need be followed because energy loss depends primarily on charge. In galactic propagation isotopic composition is measured and is invaluable in identifying the ultimate source of cosmic rays.

Our work in galactic cosmic ray propagation has centered on matrix methods. The matrix methods are applicable at cosmic ray energies above a few hundred MeV/nucleon where most cosmic rays are found. In these methods an elegant separation between the small-scale physics of particle interactions and the large-scale astrophysics of propagation is possible. All of the particle interactions are incorporated into a "modification matrix". Once this matrix has been developed, propagation is accomplished using matrix routines and various pathlength distribution integrations.

The problems encountered in galactic cosmic ray propagation may be outlined as follows:

1. Modification matrix construction

   i. Develop a list of isotopes which decay slowly and must be followed independently in propagation.
   ii. Model and compute the total and partial fragmentation cross sections of nuclei on H and He (the major components of the interstellar medium).
   iii. Model and compute the stopping power of high-energy ions in the interstellar medium.
   iv. Compute the decay rates of cosmic rays. These rates are subject to relativistic time dilation, and the relative rates of stripping and attachment of electrons.

v. Construct a matrix of uncertainties in all modification matrix components.

2. Compute arriving cosmic ray flux as a function of various astrophysical parameters

i. Solve the propagation problem by diagonalization or inversion of the modification matrix.
ii. Compute flux outside heliosphere by integrating over a pathlength distribution.
iii. Modify fluxes according to the modulation by the solar wind.
iv. Compute primary and secondary contributions to the arriving flux.
v. Compute errors in all fluxes.

The model of galactic cosmic ray propagation outlined above allows many astrophysical hypotheses to be explored. Most of the preparation for these computations has been described in a major paper completed during this contract period ("Propagation of Heavy Cosmic Ray Nuclei"). Important results of propagations done to date are contained in "Distributed Acceleration of Cosmic Rays" and "On the Abundances of Ultraheavy Cosmic Rays".

The major deficiency in cosmic ray propagations is the lack of accurate semiempirical models of the proton-nucleus partial fragmentation cross sections. Errors in these cross sections now limit the conclusions that can be drawn from more accurate experimental results in the $Z < 29$ range (Li-Ni) where most heavy cosmic rays are found. Computations of ultraheavy cosmic ray abundances also suffer from systematic errors and inconsistencies in the partial cross section calculations.

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